MHD research, inc. FINAL REPORT

May 1964

POST OFFICE BOX 1815, NEWPORT BEACH, CALIFORNIA

DISTRIBUTION OF ENERGY IN A SHOCK TUBE DRIVER

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Contract NAS2-1831

Submitted by T. J. Naff
Principal Investigator
MHD RESEARCH, INC.
P. O. Box 1815
Newport Beach, California

MHD Report No. 652

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1. INTRODUCTION AND OBJECTIVE OF THE PROGRAM

During several meetings with NASA-Ames personnel, the problem of heating a very long shock tunnel driver to temperatures, above those attainable through chemical combustion in the driver, was discussed. Only two methods appeared feasible; direct electrical heating of the entire volume of the driver, or energy distribution throughout the volume by wave motion. In the latter case electrical heating would be utilized to heat a portion of the tube and wave motion would then distribute the energy. Because of the technical simplicity (lower operating voltage) and possible savings in cost, the latter case (wave distribution) was the subject of a series of tests in a scaled down version of the proposed Ames driver facility.

The primary objective of the program was to determine the pressure-time history at selected positions in a high pressure driver and the efficiency of energy input of the wave heating process. This objective was met during the program.

2. SIMULATION CAPABILITY

The proposed full-scale Ames shock tunnel driver (referred to as Mark I in the following) will have a 4.5 foot arc (e.g., spark) at one end of a 10 foot long tube of 4 inch inside diameter. The proposed energy source, E, for the system is a one megajoule capacitor bank at 40 KV. The following calculations then, serve to justify the ability of a scaled down system at MHD Research, Inc., to properly simulate the proposed system.

The volume of the Mark I driver is:

$$V = 1510 \text{ in}^3 ,$$

corresponding to an energy density of

$$\frac{E}{V} = \frac{10^6}{1510} = 661 \text{ joules/in}^3 .$$

The maximum design pressure of the Mark I driver will be on the order of 10,000 psi. (Taken hereafter to be 7500 psi to allow a margin of safety).

Several types of simulation have been discussed between NASA and MHD Research, Inc. personnel, including wave simulation only, (e.g., a time study of the wave motion), temperature-pressure simulation only, a combination of the above, and finally "complete simulation". Defining complete simulation is, however, a matter for discussion.

After careful consideration, the following simulation scheme, for which the equipment at MHD Research, Inc. was capable of achieving the desired performance, was considered most appropriate.

1. Simulate the length to area ratio of the proposed driver.

2. Si mulate the ratio of the heated volume to total volume.
3. Limit calculated instantaneous input temperatures to 15,000° K to prevent excessive radiation cooling.
4. Limit calculated instantaneous input pressures to 7500 psi.

Now the length to area ratio of the Mark I driver is

$$\frac{\ell}{A} = \frac{120}{12.6} = 9.5 \text{ in}^{-1} \quad .$$

Therefore for a 2 inch inside diameter simulator

$$\ell = 9.5(A) = (9.5)(3.14) = 30 \text{ inches}$$

The volume of the simulator is then

$$V_s = \frac{\pi(2)^2}{4}(30) = 94 \text{ in}^3 = 1550 \text{ cm}^3 \quad ,$$

and the total energy required, E_s, is

$$E_s = (661 \text{ joule/in}^3)(94) = 62,000 \text{ joules}$$

This energy is available at MHD Research, Inc. in a 11 KV capacitor bank.

The maximum length of discharge for a 11 KV bank is about 10 inches. Therefore, the ratio of the heated volume to total volume is

$$\frac{V_h}{V_t} = \frac{\ell h}{\ell t} = \frac{10}{30} = 0.33 \, .$$

For the proposed 10 foot driver this corresponds to a 3.3 foot arc, which is entirely feasible for the 20-40 KV system envisioned for the Mark I.

To limit the peak temperatures and pressures, the initial loading density is important. This density/pressure can be calculated as follows, assuming helium as an ideal charging gas and energy input times short compared to wave motion times in the gas:

Given, $p_f = 7500 \text{ psi} = 510 \text{ atm}$

$T_f = 15{,}000^\circ \text{ K}$

$R_o = 0.08206 \dfrac{\text{liter-atm}}{\text{g-mole-deg}}$, or, $8.314 \dfrac{\text{joule}}{\text{deg-mole}}$

MW = 4.003 for helium.

Therefore, the helium density is

$$\rho = \frac{pM}{R_o T} = \frac{(510)\,(4.003)\,(10^{-3})}{(0.08206)\,(15{,}000)}$$

$$= 1.66 \cdot 10^{-3} \text{ g/cm}^3 \text{ (initial charging density).}$$

Since all energy addition goes into internal energy for an ideal gas, the necessary energy per gram (ΔW) to raise the gas in the heated volume to $15{,}000^\circ$ K can be calculated as follows:

Given, $T_i = 290^\circ \text{ K}$

$$\Delta W = 3/2 \frac{R_o}{M} (T_f - T_i)$$

$$\Delta W = 3/2 \frac{(8.314)\,(15{,}000 - 290)}{4.003}$$

$$\Delta W = 45{,}700 \text{ joules/g.}$$

The required energy density is

$$\frac{E}{V} = \Delta W \rho = (45.7 \cdot 10^3)(1.66 \cdot 10^{-3})$$

$$\frac{E}{V} = 76.0 \text{ joule/cm}^3.$$

The heated volume, V_k, for the present 5 cm diameter simulator is

$$V_k = \frac{\pi (5)^2}{4} (25) = 492 \text{ cm}^3 .$$

The energy necessary to raise the temperature of the heated portion of the simulator to 15,000° K while limiting the pressure to 7500 psi is:

$$E = \left[\frac{E}{V_k}\right] V_k = (76)(492) = 37,400 \text{ joules.}$$

This energy, if distributed uniformly by wave motion, will leave a net total temperature calculated as follows:

$$\Delta W_{total} = \frac{(37.4 \cdot 10^3) \text{ joules}}{(1.66 \cdot 10^{-3} \frac{g}{cm^3})(1.55 \cdot 10^3) \text{ cm}^3} = 1.45 \cdot 10^4 \frac{\text{joule}}{g}$$

$$T_{total} = 2/3 \, \Delta W_{total} \frac{M}{R_o} + T_i = 2/3 (1.45 \cdot 10^4) \left[\frac{4.003}{8.314}\right] + 290$$

$$T_{total} = 4970^\circ \text{ K} = 8947^\circ \text{ R} \quad \text{(driver design temperature)}$$

The initial charging pressure at room temperature is:

$$P_i = \left[\frac{1.66 \cdot 10^{-3}}{4.003}\right]\left[\frac{0.08206}{10^{-3}}\right] (290) = 9.85 \text{ atm.}$$

$$P_i = 155 \text{ psia.}$$

The final calculated pressure is:

$$P_{f_{(calc)}} = \rho \frac{R}{M} T$$

$$P_{f_{(calc)}} = (1.66 \cdot 10^{-3})(20)(4.97 \cdot 10^{3}) \text{ atm}$$

$$P_{f_{(calc)}} = 165 \text{ atm} = 2430 \text{ psia.}$$

The following table shows the simulation parameters of interest for the Mark I driver compared to the simulating tubes.

Tube	Length	Arc Length	ℓ/A	Arc length/ℓ
(Mark I)	10 feet	4.5 feet	9.5 in^{-1}	0.45
MHD #1	17 inches	8 inches	5.4 in^{-1}	0.447
MHD #2	30 inches	10 inches	9.5 in^{-1}	0.33

Therefore, it can be seen that the 30 inch MHD tube simulates the length to area of the proposed facility while the 17 inch tube simulates the arc length to total length ratio. A 78 inch tube was also used with a 10 inch arc to observe the achievement of pressure equilibrium in a very long tube.

Photomultiplier traces of light emitted by the luminous gases were taken through quartz window ports for analysis by NASA personnel.

Using the facility as herein proposed would allow complete simulation at all pertinent parameters of interest in the large one megajoule facility.

The initial test program for this type of complete simulation has provided

$$P_f \text{ vs } E$$

and

$$P_f \text{ vs } P_i$$

choosing values of interest, where P_f is the final equilibrium pressure, E the input energy, and P_i the initial charging pressure.

3. DESCRIPTION OF APPARATUS

The energy storage unit consists of 48 capacitors, each having a capacitance of 27.5 microfarads and a voltage rating of 15 KV. Each capacitor is connected to a coaxial collector system by a 10 foot length of RG 8/U cable. The outer ground ring of the collector is bolted to the vertical support frame and the shock tube breech cap. Photographs of the capacitor bank and collector are shown as Figures 1 and 2.

The two coaxial collector rings are made of welded aluminum tubing, 12.75 inch OD and 8.75 inch OD, with 0.375 inch wall thickness. Ceramic insulators 1 inch diameter by 1.5 inch long are used to support and electrically insulate the inner positive ring. Swagelok fittings are used to connect the coaxial cables to the collector.

The shock tube assembly is fabricated of 5 inch diameter carbon steel rod, drilled and bored to 2 inch ID $\pm$ .005. The original design consisted of three sections, two each 48 inches long and one 24 inches long. The end cap, breech cap and the connector nuts are made of 8 inch diameter carbon steel. All sections except the breech cap and driver end of the tube are connected with a standard machine thread. Seals are made with high pressure viton "O" rings. The driver end of the tube is inserted into the breech cap and bolted with eight 5/8 inch high strength bolts. The tube assembly is supported on wood shock insulators and transported on roller bearings. Adjusting screws provide vertical and horizontal tube alignment. Optical viewing ports and transducer ports are provided as shown in Figures 4, 6 and 8. One 0.125 inch port is used for evacuating and pressurizing. Figure 3 is a photograph of the assembled shock tube.

A mechanical switch is used to initiate the discharge. The capacitor bank is connected directly across the collector ring terminals. Switching occurs when a wire which is in contact with the inside wall of the shock tube is moved near or against the face of the steel electrode. This is accomplished by attaching one end of a wire or foil to the tube liner, the other end to a nylon rod. The nylon is inserted in a central hole in the electrode and screwed into a spring loaded actuator rod. This rod is forced into the armed position and restrained by a solenoid operated cam. When the cam is released, the spring plus the initial gas pressure forces the rod to the fire position. Thus, the trigger wire makes contact with the electrode and explodes, initiating the arc.

4. EXPERIMENTAL PROCEDURE

The following is a description of a typical firing sequence of the shock tube driver:

The electrode assembly and tube bore are thoroughly cleaned with acetone and alcohol. The system is checked for damage incurred during the previous shot. A new nylon firing pin with a correct length of trigger wire or foil is installed in the electrode. A tube liner made of 0.015 inch mylar impregnated paper is rolled to form a 2 inch diameter cylinder around the electrode insulator. The trigger wire is secured (taped) to the forward end of the liner. The tube section is then rolled into the breech cap and bolted into position. The vacuum line is connected and the system is evacuated to approximately 1 mm Hg. The vacuum system valve is closed and the tube is filled with helium to the initial firing pressure. The mechanical initiator switch is locked in the "arm" position, and the instrumentation is checked and calibrated. The system is now ready for operation. The capacitor bank is then charged to the desired operating voltage. The system "fire" sequence is initiated by cam timer which also controls the operation of the instrumentation. Immediately after fire the gas is released from the tube. A complete test run can be accomplished in approximately forty-five minutes.

One test failure is worthy of note in this report.

While conducting a test on March 4, 1964, a rear electrode feedthrough failure occurred. The probable cause for this failure is stressing due to the magnetic field of the feedthrough during discharge.

The inductance of the system is:

$$L = 50 \cdot 10^{-9} \text{ henry}$$

The total energy storage is:

$$E = 80,000 \text{ joules}$$

Peak current for near damped conditions is:

$$I_{peak} \cong 2/3 \frac{CV}{2\pi\sqrt{LC}} = 2/3\ \omega CV$$

$$I_{peak} \cong 1.2 \cdot 10^6 \text{ amp.}$$

The magnetic field at the surface near the point of failure was:

$$B = \frac{2I}{10^7 a}$$

where a is the radius of the conductor in meters

$$\therefore B = 38.4 \frac{\text{Weber}}{M^2} = 384,000 \text{ gauss}$$

According to Furth, Levine, and Waniek, (RSI, 28 No. 2, Nov. 1957, p. 951) hard copper yields and becomes fluid at approximately 300,000 gauss. Also, the diamagnetic effect of the actual electrode is such that a high force tries to propel the electrode bob down the tube.

This problem was eliminated by going to steel for this feedthrough which has a higher yield strength.

5. DATA ANALYSIS

The data obtained in this program consists of oscilloscope recordings of the voltage during discharge, oscilloscope recordings of pressure with the pressure cell located at the end of the tube opposite to the arc region, and CEC oscillograph recordings of the same pressure cell but over a much longer time scale. Also, oscilloscope records were made on some tests (using a photomultiplier) of the light emitted by the hot gas at certain locations along the tube.

Since, by basic assumption, the energy input time to the arc is short compared to wave motion times in the tube, no use was made of the voltage curves except to monitor the fact that a proper discharge has taken place. Analysis of the photomultiplier traces was performed by NASA-Ames personnel and is not incorporated in this report.

The remaining data were analyzed as follows:

A typical oscilloscope pressure trace and the data point taken from it are shown in Figure 11. P_{fp} implies the final peak pressure.

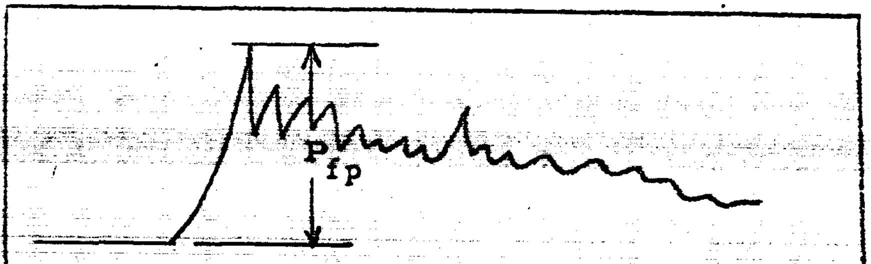

Figure 11

A typical oscillograph trace and the data points taken from it are shown in Figure 12.

$P_{\tau=0}$, $P_{\tau=10}$, $P_{\tau=30}$ imply the pressure at 0, 10, and 30 milliseconds after the initial pressure rise. These are of interest because

$P_{\tau=0}$ is the final equilibrium pressure and $P_{\tau=10}$ and $P_{\tau=30}$ indicate the cooling rates encountered for the particular conditions involved.

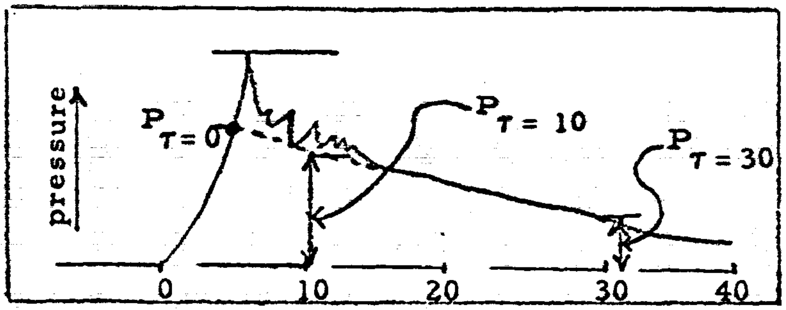

Figure 12.

The data derived from these runs are shown in Table I along with the pertinent data for the run numbers shown. Also shown in Table I are the final calculated pressure, $P_{f(calc)}$, and temperature $T_{f(calc)}$, and the efficiency

$$\left[P_{\tau=0} \Big/ P_{f_{(calc)}}\right] 100 .$$

Figure 4 is a diagram showing the physical configuration used for tests 11 through 14. Figure 5 is a plot of $P_{\tau=0}$, $P_{\tau=10}$, and $P_{\tau=30}$ vs. P_i for the data of tests 11 through 14. Figure 6 is the physical configuration and Figure 7 is a plot similar to Figure 5 for the data of Test 20 through 23. Figure 8 is the physical configuration and Figure 9 is a plot similar to Figure 5 for the data of tests 28 through 31.

The same physical set up as shown in Figure 6 was used to obtain the data of runs 24 through 27. These data are plotted as Figure 10 and shows the final pressure $P_{\tau=0}$, $P_{\tau-10}$, $P_{\tau=30}$ vs. capacitor bank energy. The energy was varied by disconnecting the proper number of capacitors from the collector such that the same voltage would be maintained.

TABLE I

Test No.	E (k joule)	ℓ (inches)	$\ell_{(arc)}$ (inches)	P_i psig	P_{f_p} psia	$P_{\tau=0}$ psia	$P_{\tau=10}$ psia	$P_{\tau=30}$ psia	$P_{f(calc)}$ psia	$T_{f(calc)}$ ^oK	Efficiency %
11	30	17	8	150	11,000	1,560	1,190	975	3,230	6,890	48.3
12	30	17	8	250	10,000	1,760	1,500	1,250	3,310	4,240	53.2
13	30	17	8	350	9,600	1,850	1,370	1,190	3,490	3,130	53
14	30	17	8	450	10,000	2,250	1,860	1,500	3,520	2,490	64
20	39.8	30	10	150	8,350	1,000	750	625	2,400	5,310	41.6
21	39.8	30	10	250	7,600	1,250	1,000	875	2,580	3,320	48.4
22	39.8	30	10	350	8,350	1,430	1,120	1,000	2,710	2,440	53
23	39.8	30	10	450	7,100	1,380	1,120	1,000	2,780	1,970	49.5
24	39.8	30	10	150	6,600	1,000	750	560	2,400	5,310	41.6
25	30	30	10	150	5,850	875	600	500	1,930	4,040	45.3
26	20	30	10	150	3,750	625	437	250	1,360	2,790	46
27	10	30	10	150	2,080	450	250	250	750	1,540	60
28	39.8	78	10	150	4,160	500	250	125	1,070	2,210	46.7
29	39.8	78	10	250	5,000	565	312	155	1,190	1,540	47.5
30	39.8	78	10	350	5,250	690	375	250	1,250	1,140	55.5
31	39.8	78	10	350	5,200	625	320	250	1,250	1,140	50

No plot of pressure vs. tube length at constant energy is included since the efficiency figures of Table I imply this data.

All calculated data of Table I were determined using methods similar to those described in Section II.

6. CONCLUSIONS

Most of the curves (Figures 5, 7, 9, and 10) could be reproduced in all their important features by assuming 45 to 50 per cent over-all efficiency in the heating process. This is somewhat misleading in the case of the 78 inch long tube with a 10 inch arc length. The wave motion in the tube continues for times greater than 30 milliseconds and once true equilibrium is reached the pressure is too low to infer a temperature of interest. The reason for the consistency of the data is the method of interpretation. An average pressure line was drawn through the pressure peaks and all data were taken from this averaged line.

No consistent cooling curves for the various cases were derived. However, in all other respects the data wereconsistent. An idea of the cooling rate can be seen from Figure 10. Note that all the lines converge (approximately) to the initial charging pressure. The curve's spacing for the first 10 milliseconds is greater than for the next 20 milliseconds indicating a high initial cooling rate which is as expected.

The following statement is a reasonably accurate summary of the results of these experiments:

If the heating times required and the wave transit times in the tubes are both less than 10 milliseconds and sufficient energy is available to allow more than 50% energy loss, then partial heating of the driver length is an acceptable method of heating a shock tube driver. This statement assumes the availability of a diaphragm or valve that will both withstand the overpressures encountered and open on command.

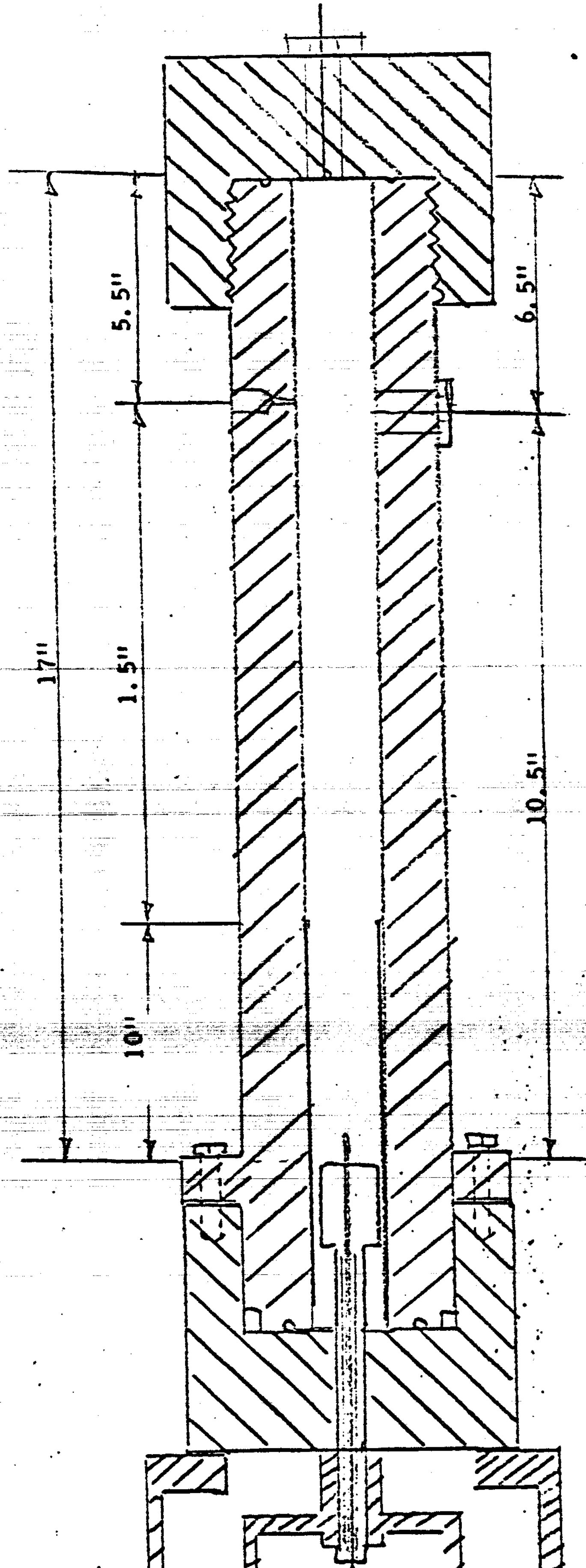

FIGURE 4. 17" TUBE

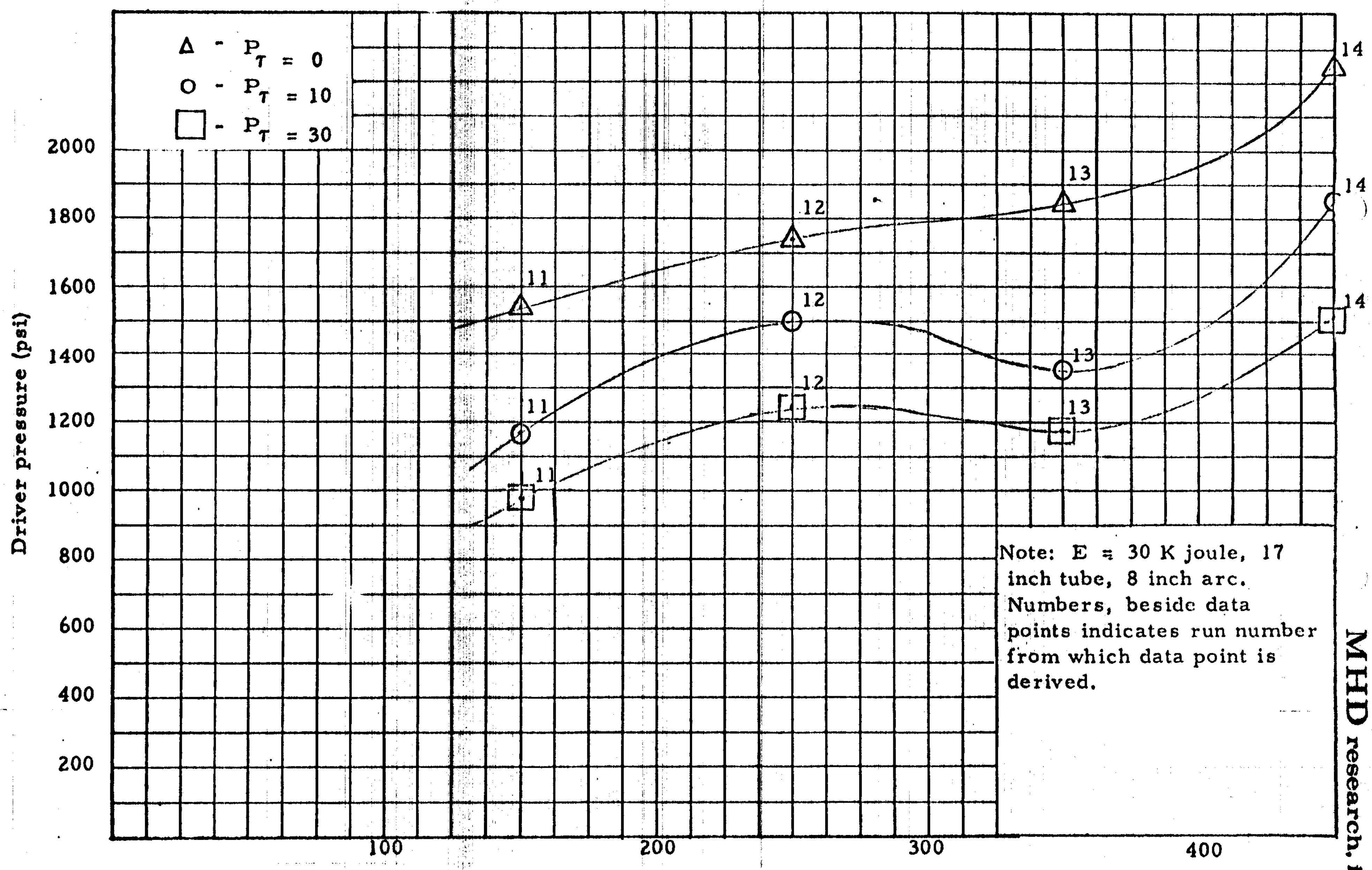

Figure 5. Initial charging pressure (P_i) - psig He

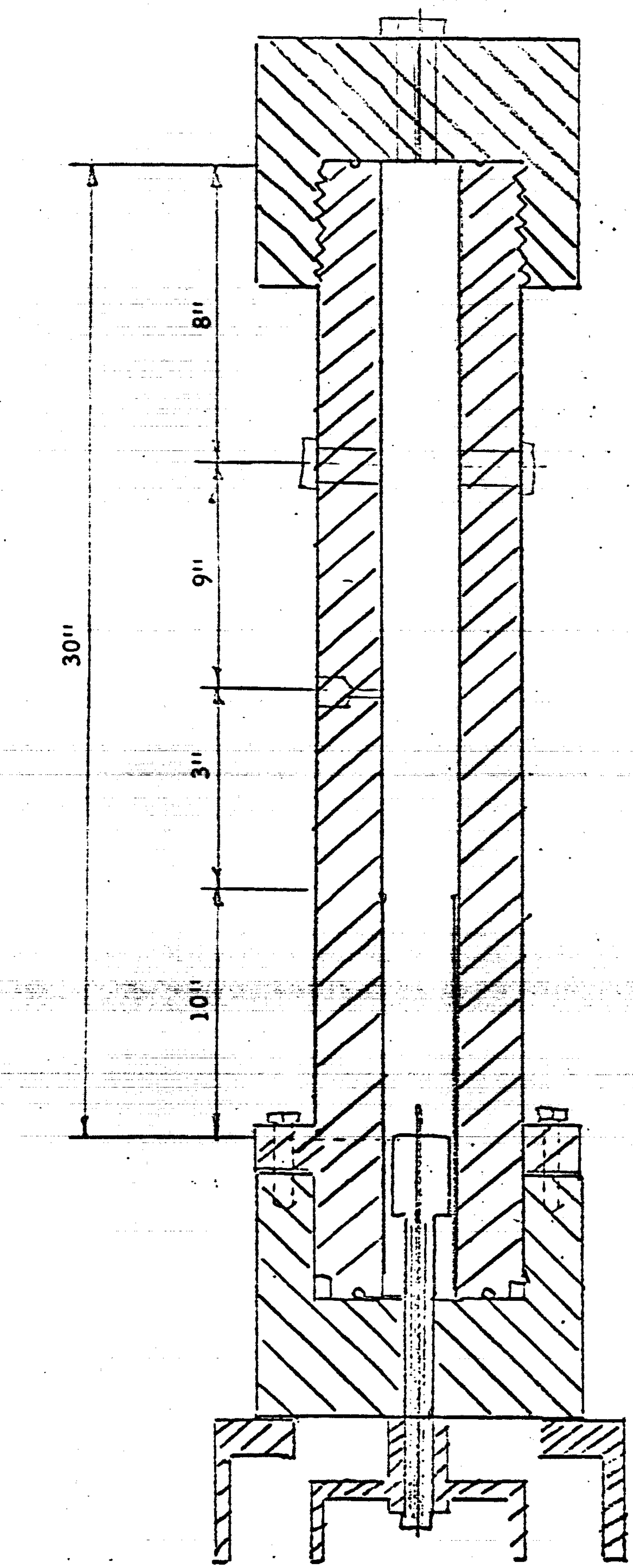

FIGURE 6. 30" TUBE

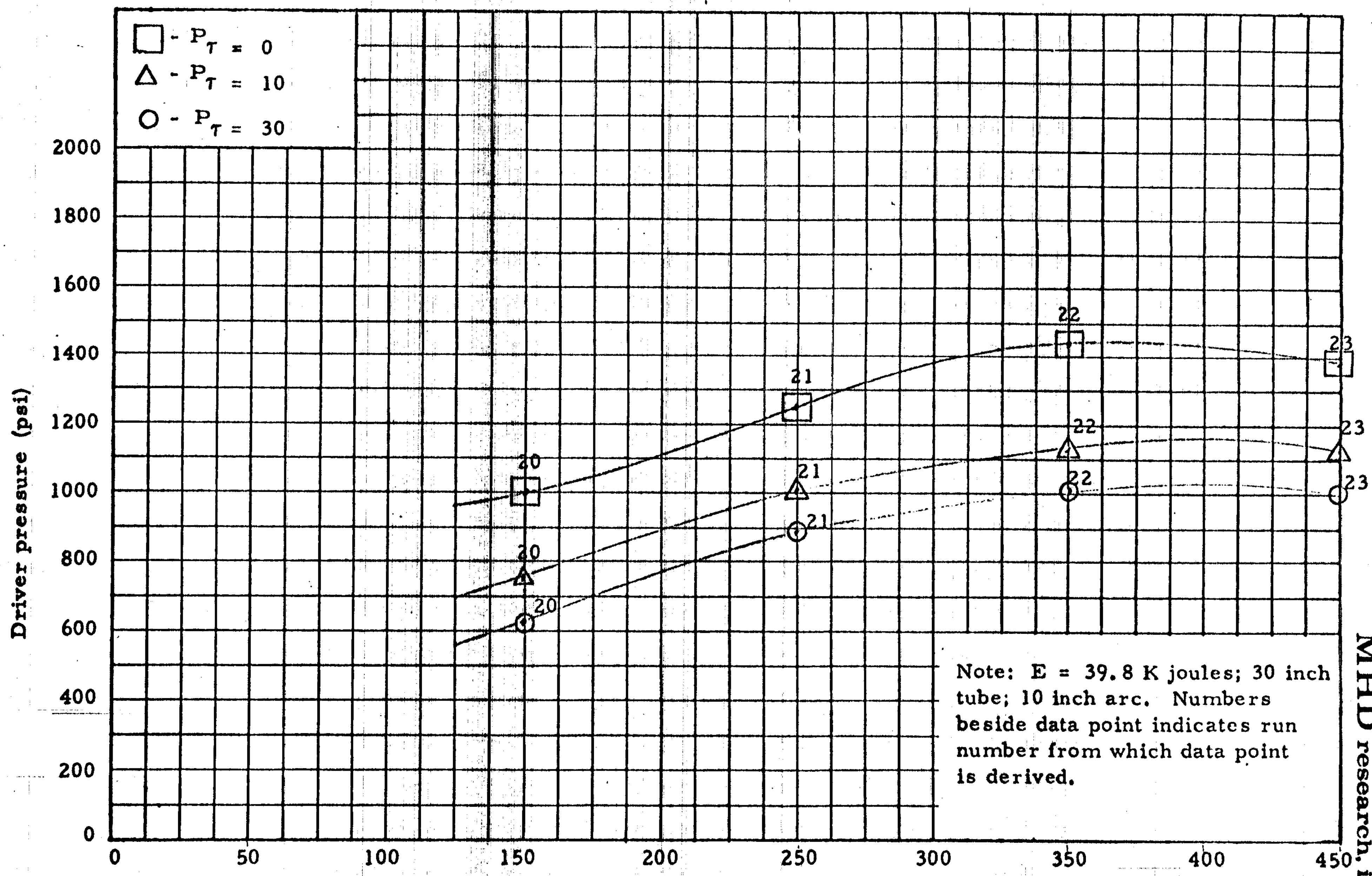

FIGURE 7. Initial charging pressure (P_i) - psig He

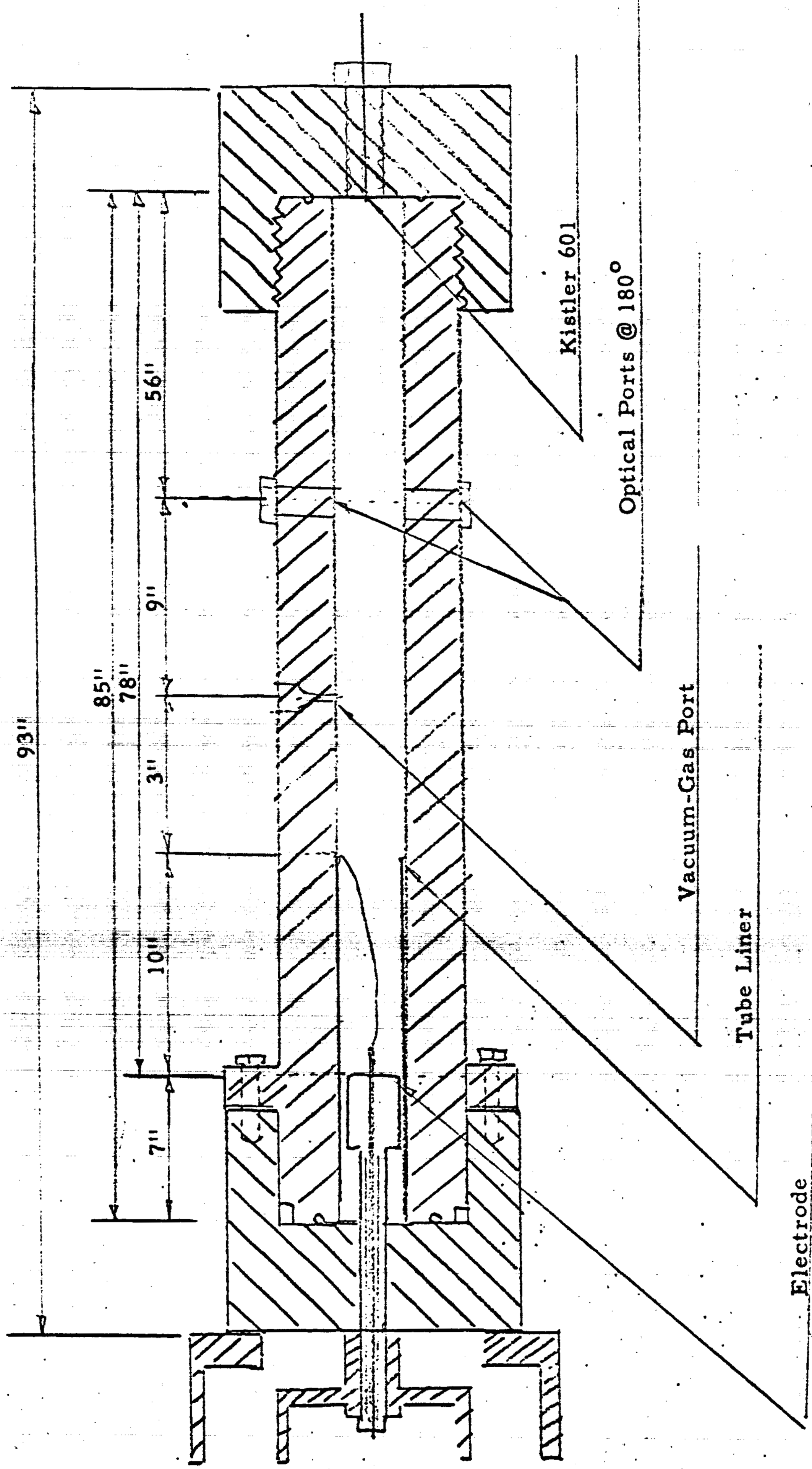

FIGURE 8. 78" TUBE

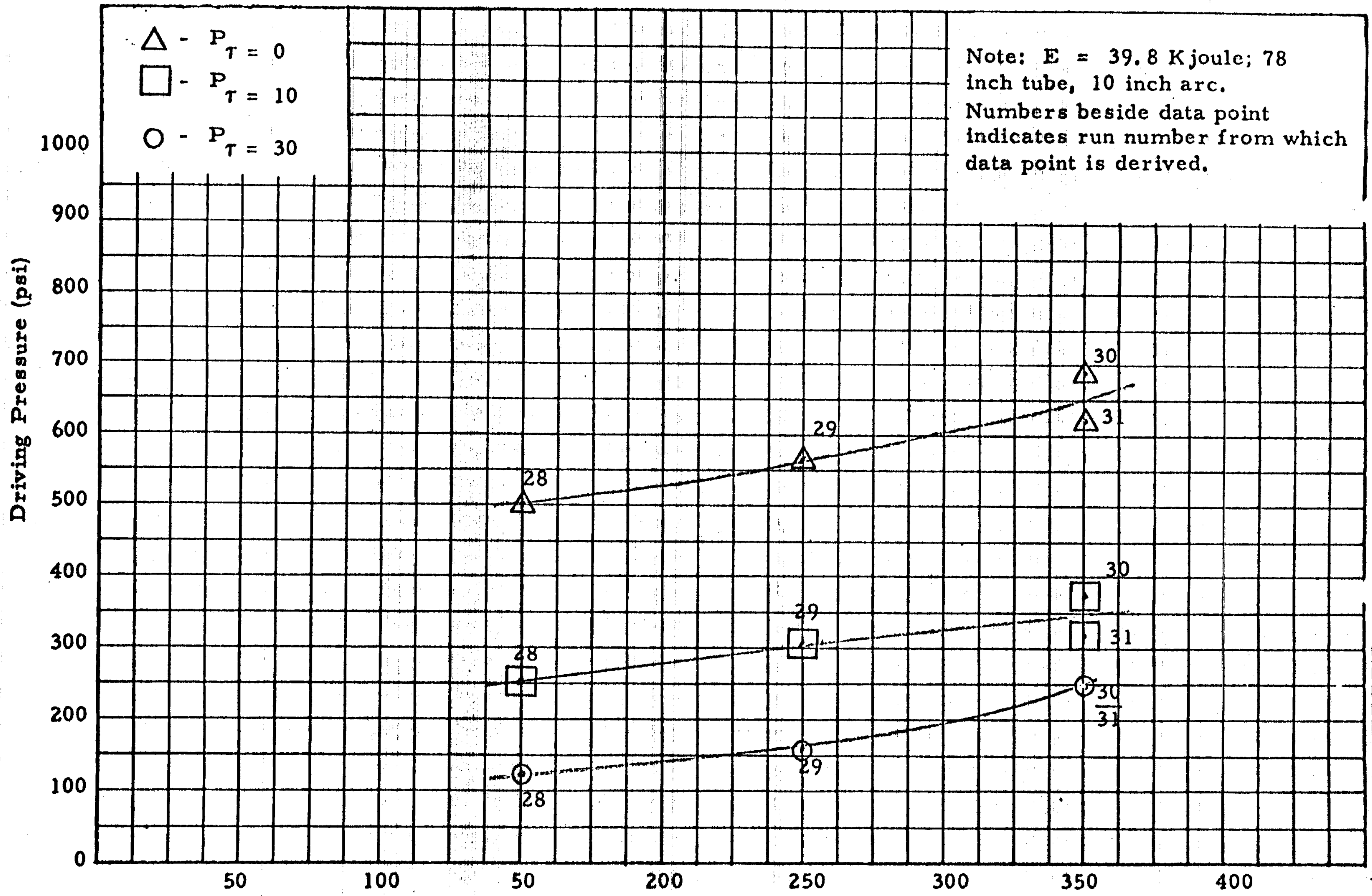

Figure 9. Initial Charging Pressure.

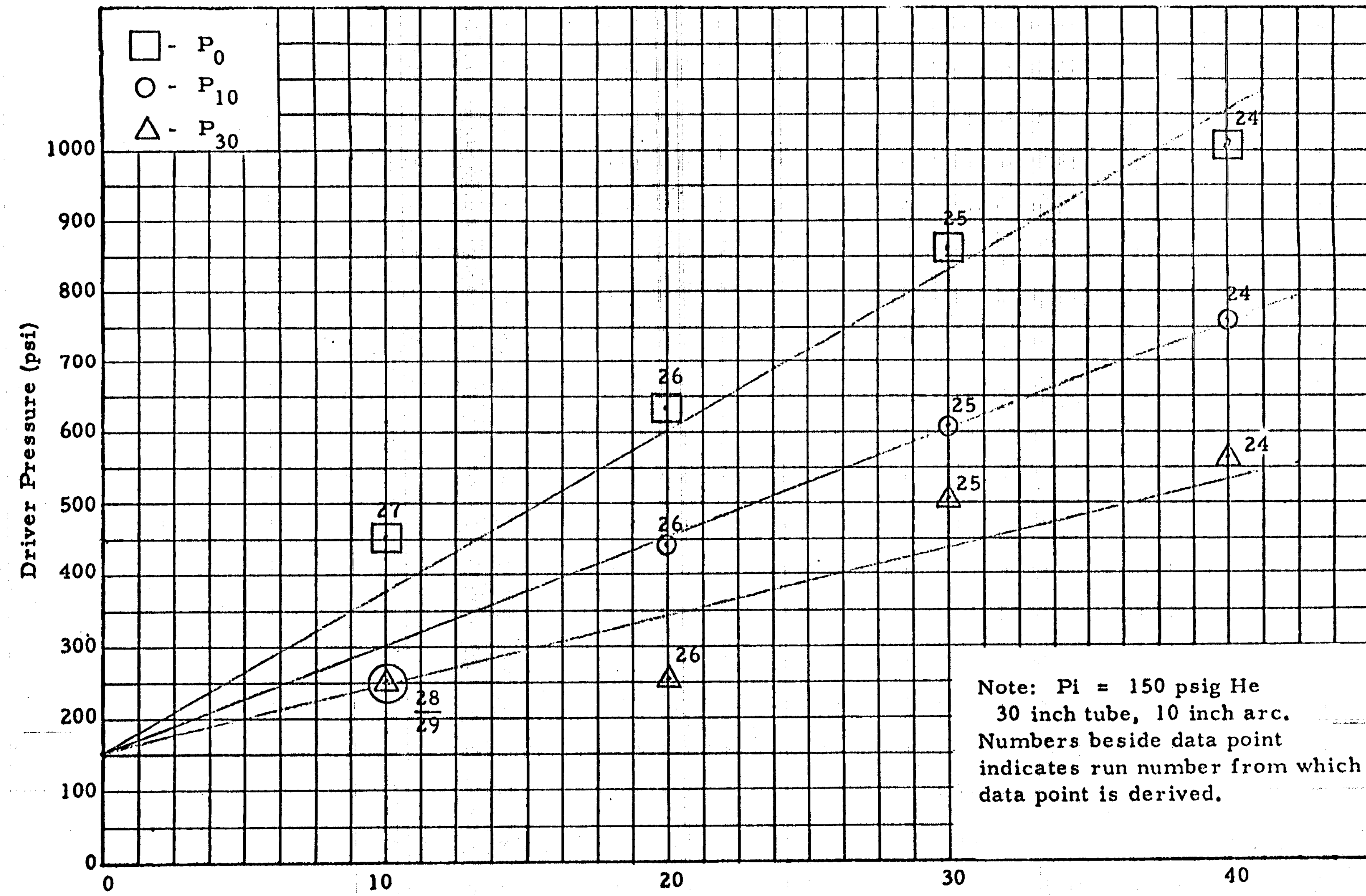

Figure 10. Capacitor Bank Energy (K joules)

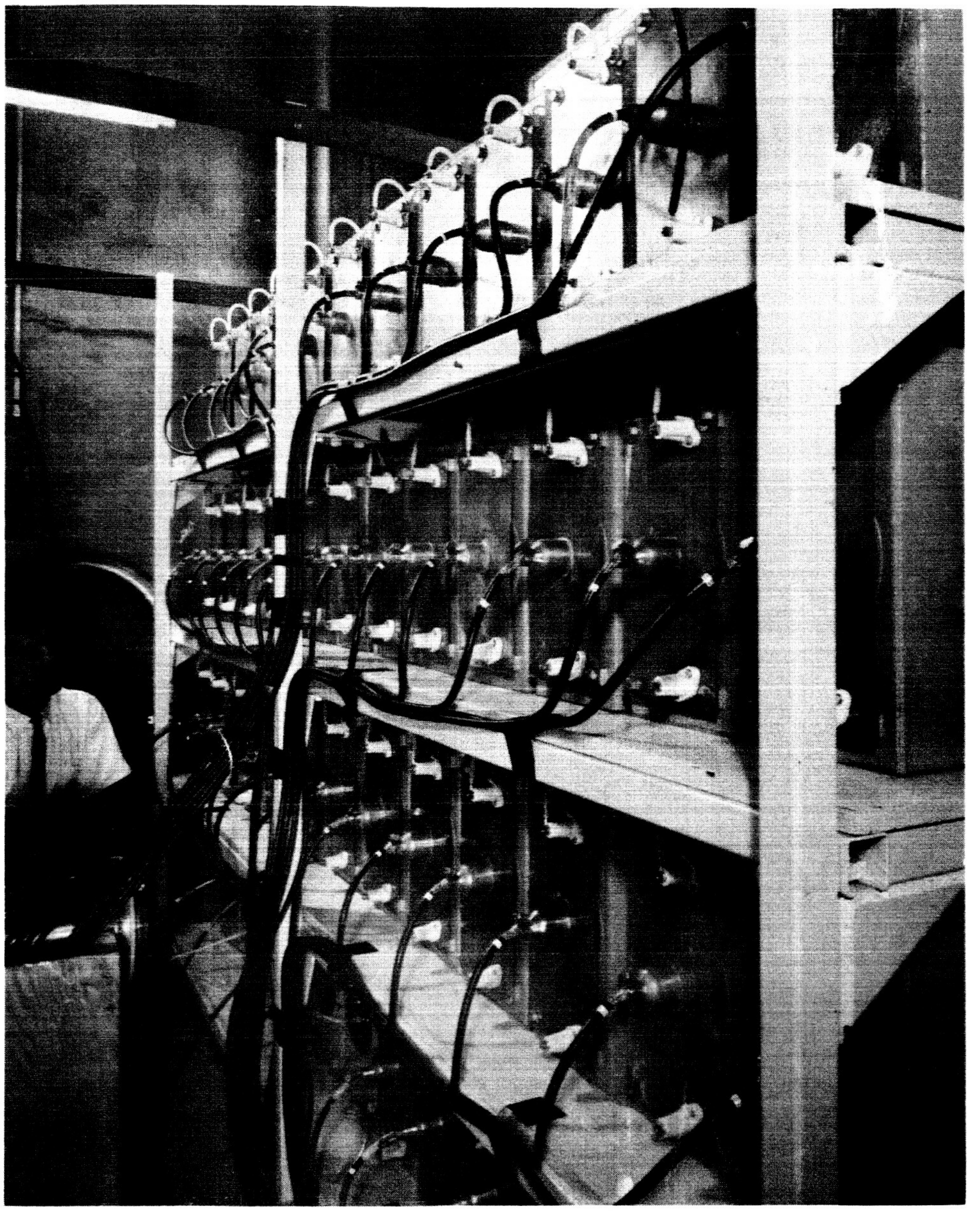

Figure 1. Capacitor Bank

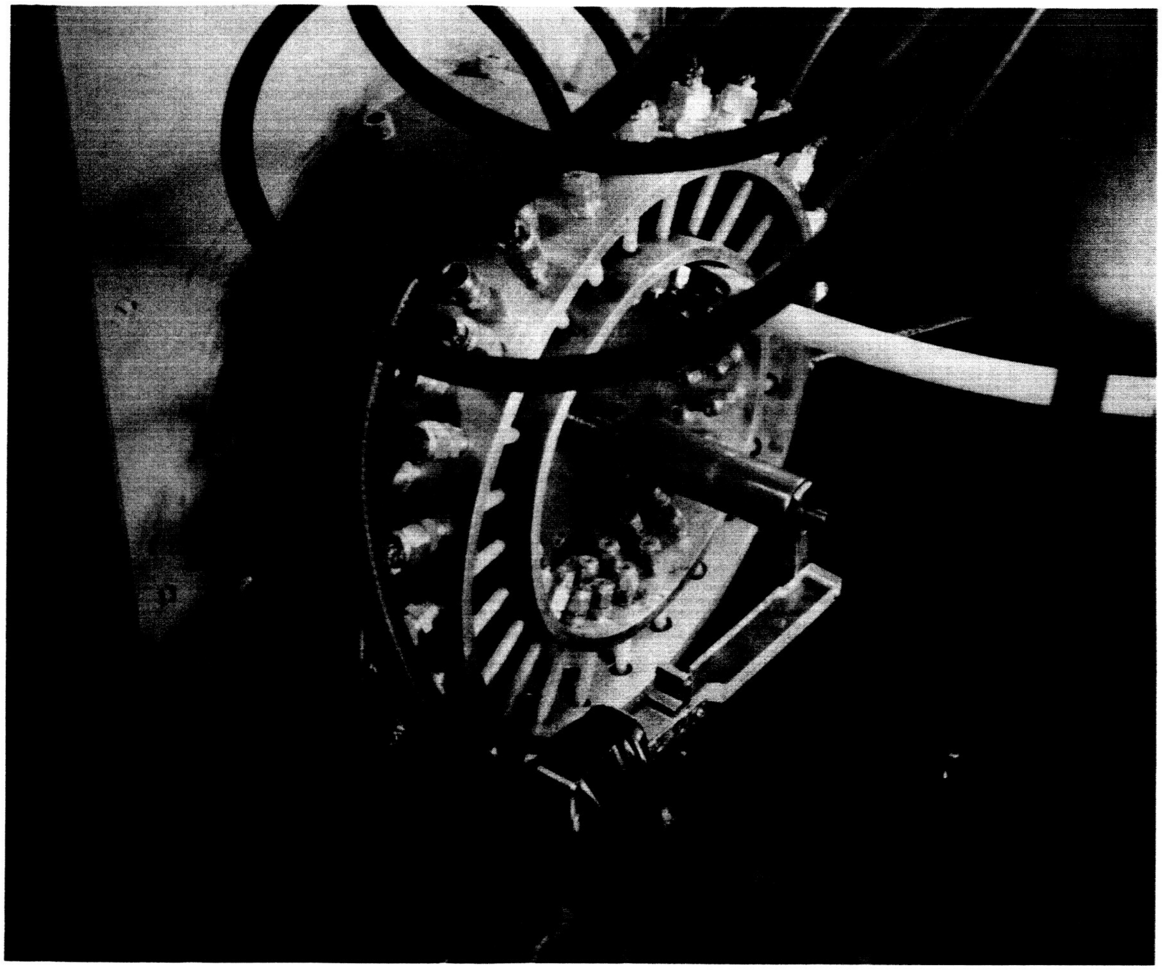

Figure 2. Collector

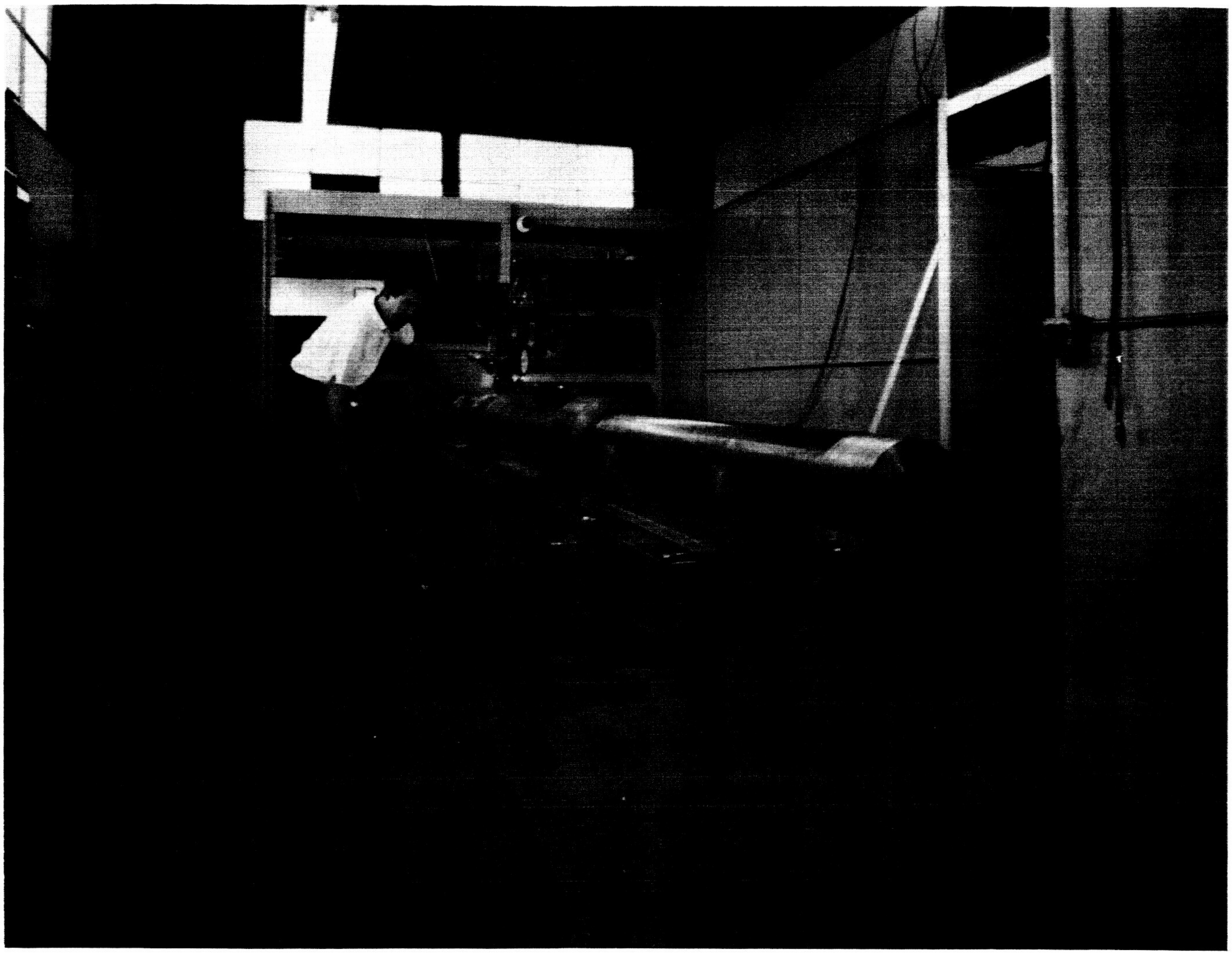

Figure 3. Shock Tube